

Magnetically confined electron columns and high-energy hadron beams

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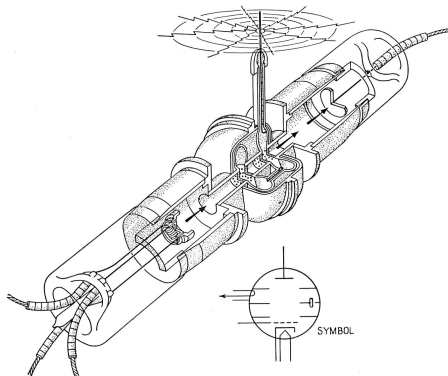


In collaboration with

- A. Drozhdin, V. Shiltsev, D. Still, A. Valishev, L. Vorobiev (FNAL)
- G. Kuznetsov, A. Romanov (BINP Novosibirsk)
- J. Smith (SLAC)

keV electron beams

Electron beams with keV kinetic energies studied in detail in 1930s–1950s for development of vacuum tubes: diodes, triodes, cathode-ray tubes, microwave and radar devices (magnetrons, klystrons, traveling-wave tubes), phototubes

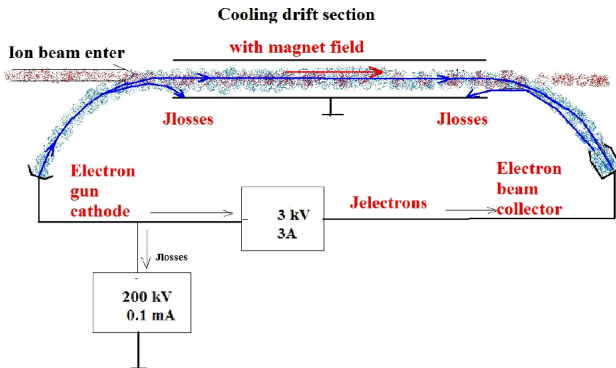


Spangenberg, Vacuum Tubes (McGraw-Hill, 1948)

Pierce, Theory and Design of Electron Beams (Van Nostrand, 1954)

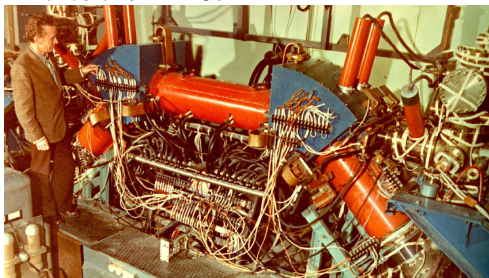
Electron cooling

- Successful application of keV electron beams to accelerator science
- For ions, radiative cooling and ionization cooling are not available (high mass, nuclear interactions)
- Electron cooling proposed by Budker in 1965 as a means to cool antiprotons for colliders



Electron cooling

- Cold magnetically confined electron beam overlaps hot ion beam with same velocity, acting as comoving medium without nuclei
- Heat is exchanged by Rutherford scattering
- Demonstrated in Novosibirsk in 1974



- Many facilities built around the world for the cooling of protons (COSY Jülich, ...), ions (TSR Heidelberg, ...), antiprotons (LEAR at CERN, Recycler at Fermilab, ...)

Poth, Phys. Rep. **196**, 135 (1990)

Parkhomchuk and Skrinsky, Rev. Acc. Sci. Tech. **1**, 237 (2008)

The Fermilab accelerator complex

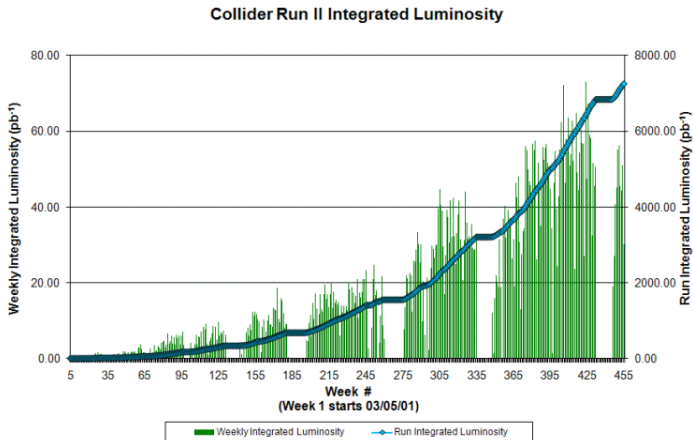


The Tevatron collider



- Kinetic energy: 150 GeV \rightarrow 980 GeV
- 1 km radius, 21 μ s revolution period
- Hundreds of superconducting magnets at liquid helium temperature
- 8 Cu 53 MHz rf cavities, 1113 buckets
- 3×12 proton bunches collide with 3×12 antiproton bunches at two collision points (CDF and D0 detectors)
- Bunch spacing is 396 ns
- Peak intensity: 3×10^{11} p/bunch, 1×10^{11} \bar{p} /bunch
- Peak luminosity: 3×10^{32} cm $^{-2}$ s $^{-1}$

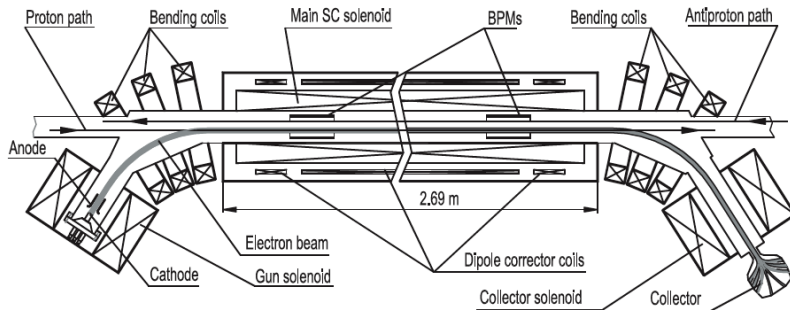
Collider performance 2001-present



Aiming at 12 fb^{-1} by October 2011.

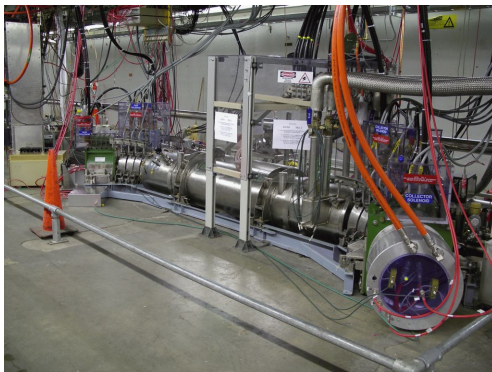
Tevatron electron lenses

- Colliding beams experience nonlinear focusing in interaction region
- Tevatron electron lenses built to compensate for beam-beam effect experienced by antiprotons



Existing Tevatron electron lenses

TEL1 used for normal operations; TEL2 as backup and for studies



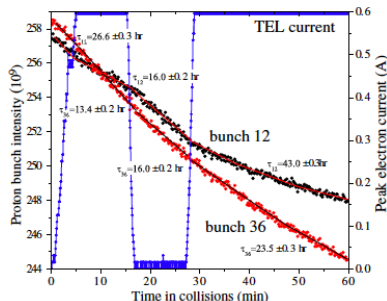
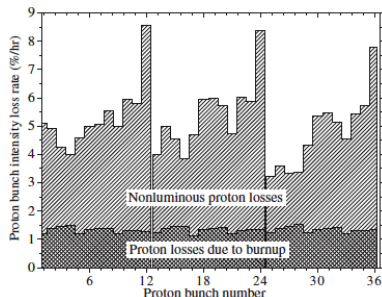
Typical parameters

Peak energy	10 kV
Peak current	3 A
Max gun field B_g	0.3 T
Max main field B_m	6.5 T
Length L	2 m
Rep. period	21 μ s
Rise time	<200 ns

Shiltsev et al., Phys. Rev. ST AB 11, 103501 (2008)

Performance of Tevatron electron lenses

- Beam-beam compensation for antiprotons not needed after implementation of electron cooling in Recycler Ring
- Demonstrated improvement of beam lifetime of individual proton bunches by shifting of betatron frequencies



- Now routinely used for clearing of 2.6- μ s abort gap between bunch trains
- Reliable instrument; alignment and current stability are critical

Shiltsev et al., *Phys. Rev. Lett.* **99**, 244801 (2007)

Shiltsev et al., *New J. Phys.* **10**, 043042 (2008)

New applications?

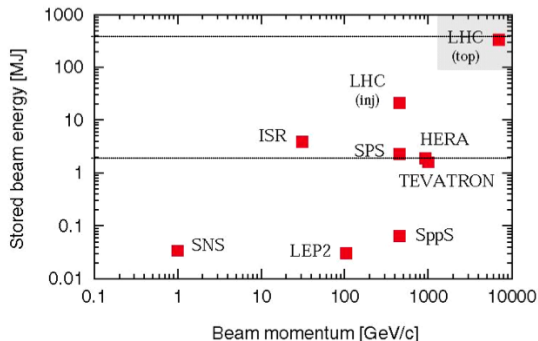
We are investigating two new applications of the interaction between magnetically confined electrons and high-energy proton beams:

- 1 Collimation with hollow electron beams
- 2 Space-charge compensation with trapped electron columns generated by beam-induced rest-gas ionization

Hollow-beam collimation

Motivation

- In high-energy colliders, stored beam energy can be large



- Beam-beam collisions, intrabeam scattering, beam-gas scattering, rf noise, resonances, ground motion, etc. contribute to formation of **beam halo**
- Uncontrolled particle losses of even a small fraction of the circulating beam can damage components, quench superconducting magnets, produce intolerable experimental backgrounds

Motivation

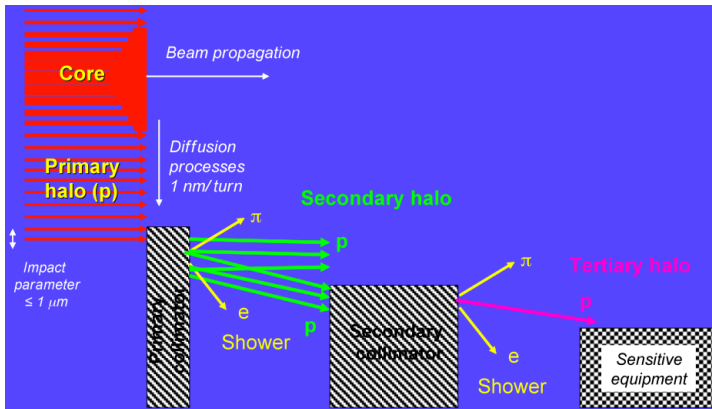
Goals of collimation:

- 1 reduce beam halo
- 2 concentrate losses in absorbers

Conventional schemes:

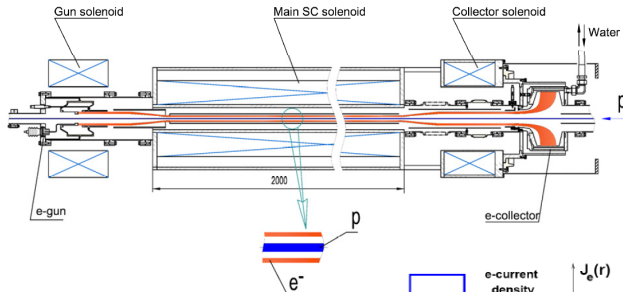
collimators (5-mm W at 5σ in Tevatron,
0.6-m carbon jaw at 6σ in LHC)

absorbers (1.5-m steel jaws at 6σ in Tevatron,
1-m carbon/copper at 7σ in LHC)



Concept of hollow electron beam collimator (HEBC)

Cylindrical, hollow, magnetically confined, pulsed electron beam overlapping with halo and leaving core unperturbed



Halo experiences nonlinear transverse kicks

Shiltsev, BEAM06, Yellow Report CERN-2007-002
Shiltsev et al., EPAC08

Requirements and constraints

- Placement: $\sim 4\sigma$ + field line ripple (~ 0.1 mm)
- Transverse compression controlled by field ratio B_m/B_g ; limited by min B_g (depends on current) and max B_m (~ 10 T)
- large amplitude functions (β_x, β_y) to translate transverse kicks into large displacements
- if proton beam is not round ($\beta_x \neq \beta_y$), separate horizontal and vertical scraping is required
- cylindrically symmetric current distribution ensures zero E-field on axis; if not, mitigate by:
 - segmented control electrodes near cathode
 - $\mathbf{E} \times \mathbf{B}$ drift
 - different core/halo tunes

Hollow-beam collimation concept

Advantages

- electron beam can be placed closer to core ($\sim 3-4\sigma$)
- no material damage
- lower impedance, no instabilities
- position controlled by magnetic field, no motors or bellows
- gradual removal, reduction in loss spikes
- no ion breakup
- transverse kicks are not random \rightarrow resonant pulsing, halo tune shift/spread
- established technological and operational experience with Tevatron electron lenses

Hollow-beam collimation concept

Disadvantages

- kicks are small, large currents required
- alignment of electron beam is critical
- hollow beams can be unstable

Transverse kicks

$$\theta_{max} \simeq \frac{2 I L (1 \pm \beta_e)}{r_{max} \beta_e c} \frac{1}{v_p (B\rho)_p} \left(\frac{1}{4\pi\epsilon_0} \right) \quad \begin{array}{l} - \text{ copropagating} \\ + \text{ counterpropagating} \end{array}$$

Example ($\mathbf{v}_p \cdot \mathbf{v}_e > 0$)

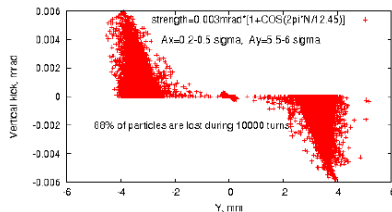
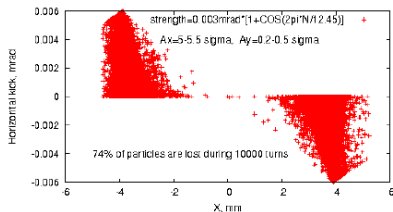
$I = 2.5 \text{ A}$ $L = 2.0 \text{ m}$ $\beta_e = 0.19 \text{ (10 kV)}$ $r_{max} = 3.5 \text{ mm (} 5\sigma \text{ in TEL2)}$

p energy (TeV)	0.150	0.980	7
kicks (μrad):			
hollow-beam max	2.4	0.36	0.051
collimator rms (Tevatron)	110	17	
collimator rms (LHC)			4.5

Simulation of HEBC in Tevatron

A. Drozhdin

- STRUCT code, complete description of element apertures, helices, rf cavities, sextupoles
- Halo defined as $[5\sigma < x < 5.5\sigma, 0.2\sigma < y < 0.5\sigma]$ or $[0.2\sigma < x < 0.5\sigma, 5.5\sigma < y < 6\sigma]$
- Hollow beam $5\sigma < r < 6.4\sigma$
- Resonant pulsing



θ_{max}

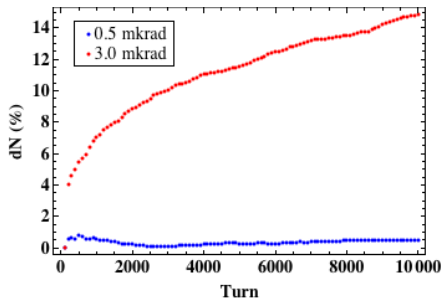
Halo losses

0.3 μ rad	28% in 200,000 turns
3.0 μ rad	80% in 10,000 turns

Simulation of HEBC in Tevatron

A. Valishev

- Lifetrac code with fully-3D beam-beam, nonlinearities, chromaticity
- Simplified aperture: single collimator at 5σ
- Halo particles defined as ring in phase space with $3.5\sigma < x, y < 5\sigma$
- Hollow beam $3.5\sigma < r < 5\sigma$
- No resonant pulsing



Halo losses vs turn number for maximum kick of 0.5 μ rad and 3.0 μ rad

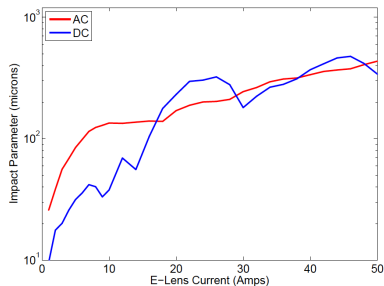
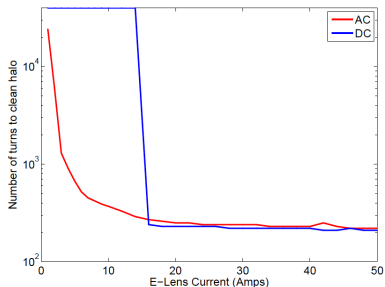
Simulation of HEBC in LHC

Smith et al., PAC09, SLAC-PUB-13745

- first_impact (1D) and SixTrack codes
- Collimator at 6σ
- Beam halo defined as ring $4\sigma < x < 6\sigma$
- Hollow beam at $4\sigma < r < 6\sigma$

cleaning \equiv 95% hits collimator

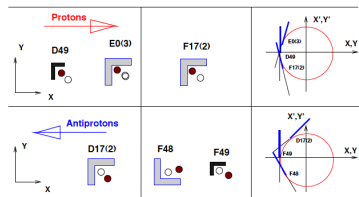
significant increase in impact parameter



Several collimation scenarios are being investigated:

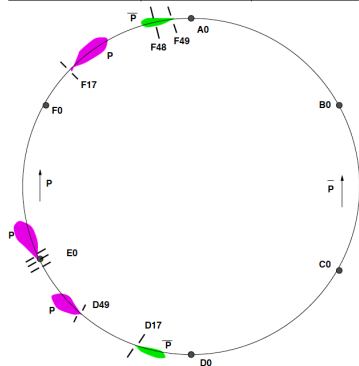
- ‘Staged’ collimation scheme: HEBC \rightarrow collimators \rightarrow absorbers
 - HEBC probably too weak to replace collimators
 - increases impact parameter
 - allows collimators to be retracted
 - can act as ‘soft’ collimator to avoid loss spikes generated by beam jitter
- Effectiveness of betatron amplitude increase for halo particles:
 - transverse kicks are weak
 - tune shifts probably too small to drive lattice resonances
 - resonant kicks timed with betatron period are very effective

Tevatron studies at 980 GeV



Possible experimental demonstrations:

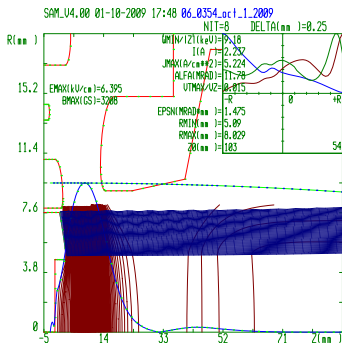
- hollow-beam alignment procedures
- effects on core lifetime
- losses at collimators, absorbers and detectors vs HEBC parameters: position, angle, intensity
- improvement of loss spikes in presence of beam jitter



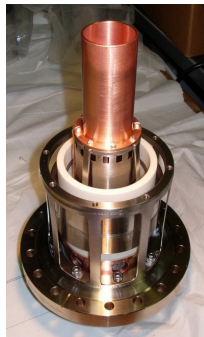
Design of 15-mm-diameter hollow gun

- several approaches to high-perveance hollow-beam design, eg immersed Brillouin cathodes (magnetron injection guns)
- present design based upon existing 0.6-in SEFT (soft-edge, flat-top) convex gun used in TEL2

Calculations with SAM code:

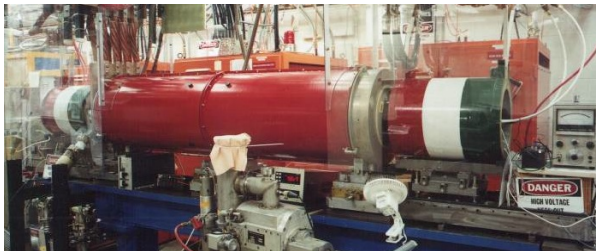


Mechanical design:



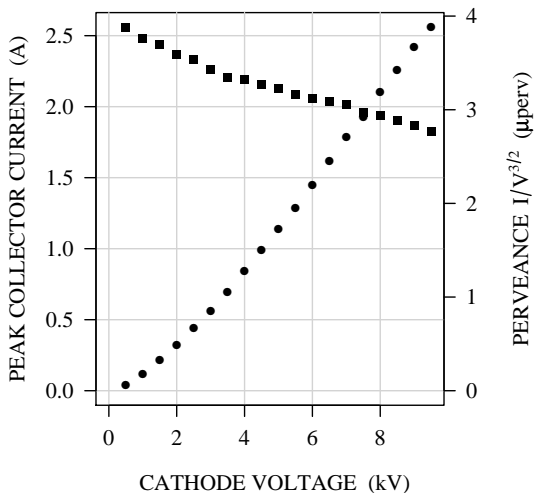
Test bench at Fermilab

Built to develop TELs, now used to characterize electron guns and to study plasma columns for space-charge compensation



- High-perveance **electron guns**: \sim amps peak current at 10 kV, pulse width $\sim \mu\text{s}$, average current $< 2.5 \text{ mA}$
- Gun / main / collector **solenoids** ($< 0.4 \text{ T}$) with magnetic correctors and pickup electrodes
- Water-cooled **collector** with 0.2-mm pinhole for profile measurements

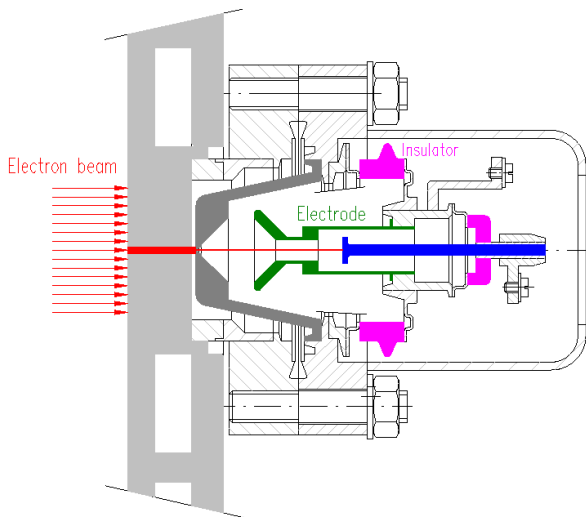
Current vs voltage of 15-mm hollow cathode



Filament heater: 66 W (1300 K)

Profile measurements

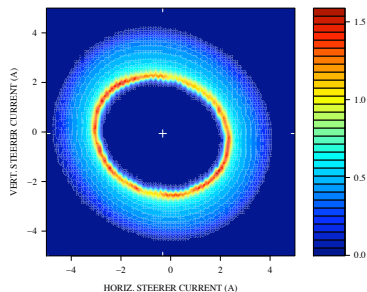
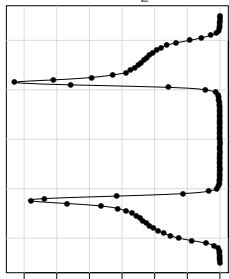
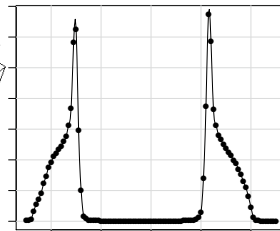
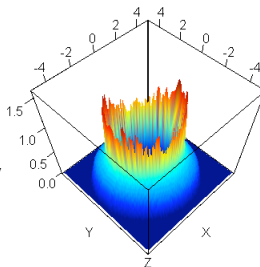
- Horizontal and vertical magnetic steerers deflect electron beam
- Current through 0.2-mm-diam. pinhole is measured vs steerer strength



HOLLOW GUN

October 21, 2009

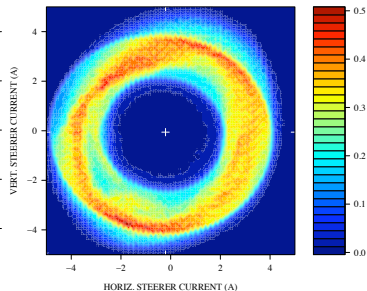
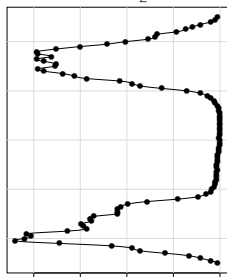
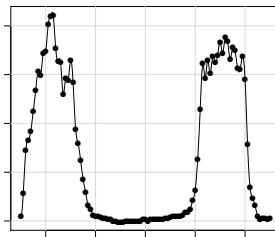
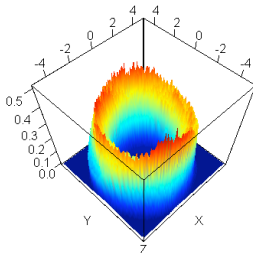
Vacuum: 2×10^{-8} mbar
 Filament: 66 W (7.75 A)
 Cathode voltage: -0.5 kV
 HV PS current: 1.0 mA
 Pulse width: 6 μ s
 Rep. period: 0.6 ms
 Peak current: 44 mA
 Solenoids: 3-3-3 kG

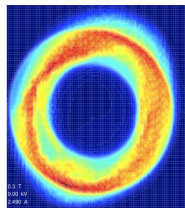
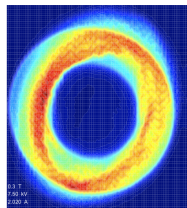
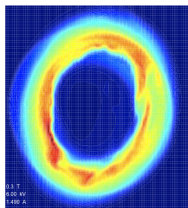
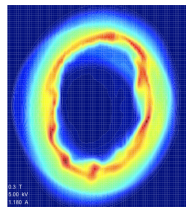
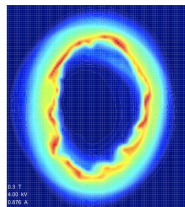
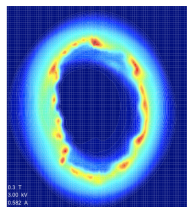
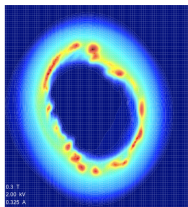
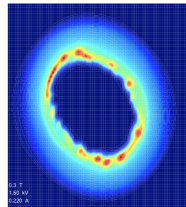
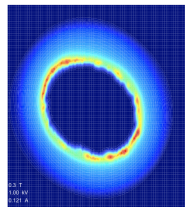
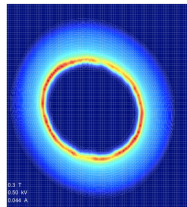
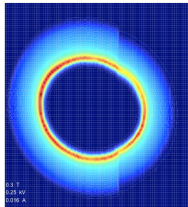


HOLLOW GUN

October 26, 2009

Vacuum: 2×10^{-8} mbar
 Filament: 66 W (7.75 A)
 Cathode voltage: -9.0 kV
 HV PS current: 1.43 mA
 Pulse width: 6 μ s
 Rep. period: 80 ms
 Peak current: 2.5 A
 Solenoids: 3-3-3 kG



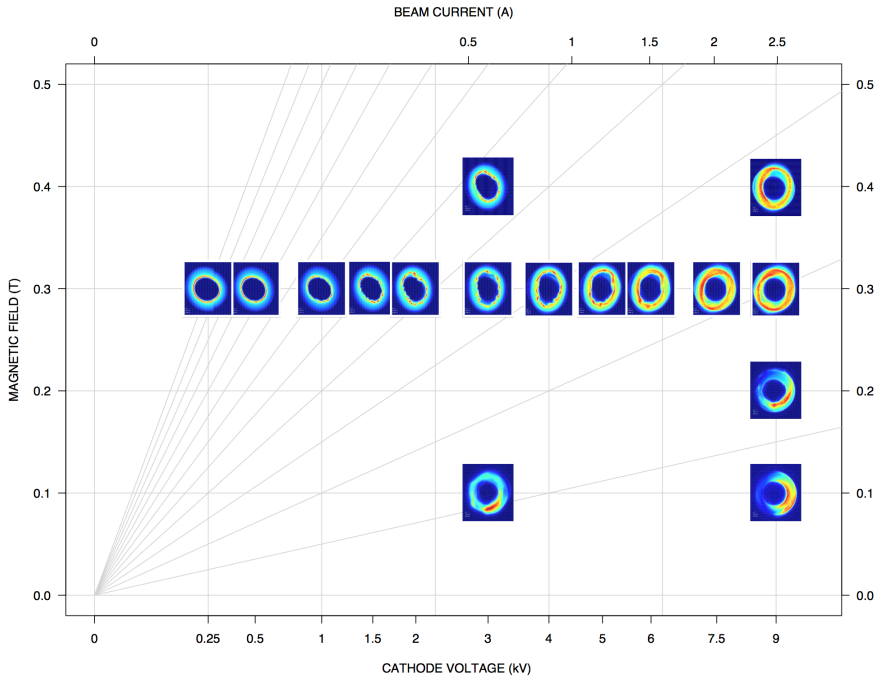


Hollow-beam instabilities

- Profiles measured 2.5 m downstream of cathode
- Magnetic field kept constant at 0.3 T
- Space-charge forces are not uniform
- As current increases, vortices appear
- Electron beam behaves like incompressible, frictionless 2D fluid
- $\mathbf{E} \times \mathbf{B}$ drift velocities depend on r
- Typical plasma slipping-stream ('diocotron') instabilities arise

Scaling properties:

- From dimensional analysis of fundamental equations one expects $I \sim V^{3/2}$ (Child-Langmuir law)
- Also, to preserve transverse profiles ($\sim L$), one finds $B \sim V^{1/2} \sim I^{1/3}$



- Extremely stable and reproducible profiles
- Good agreement of transverse profiles with expected scaling
- Intriguing beam physics (already well known?)
- Can one exploit the vortices to make a high-brightness electron source?
- Are these profiles good enough for collimation? Is stabilization needed?
- Research continues...

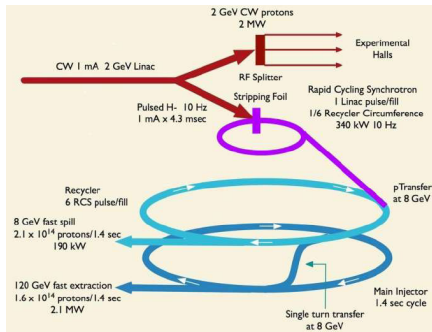
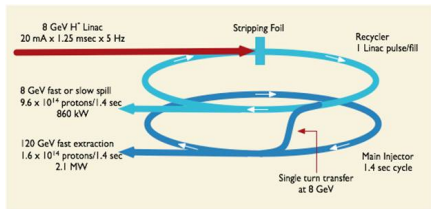
Next steps

- Simulations:
 - code comparison under common scenarios
 - performance vs lattice parameters
 - uneven B-field lines
 - realistic current profiles (smooth, asymmetric, ...)
- Test bench:
 - Complete characterization of 15-mm hollow cathode
 - Study stability of hollow beam
 - Design larger cathode
- Tevatron:
 - Calibrate TEL2 BPMs with protons, electrons and antiprotons
 - Align Gaussian electron beam with protons in TEL2
 - Test abort-gap clearing
 - Measure tune-spread changes with Gaussian gun (beam-beam compensation project)
 - Install hollow gun in TEL2 (next few months?)
 - Start parasitical and dedicated studies

Space-charge compensation with electron columns

Motivation

- Fermilab's plans to lead accelerator-based neutrino and flavor physics in the next decade rely on the construction of a **multi-MW proton source** ('Project X')
- Stepping stone towards future neutrino factory, International Linear Collider or muon collider
- Two **designs** are being considered:



- One **performance limitation** is trade-off between linac cost ($\propto \gamma$) and beam losses and activation due to space charge in synchrotron ($\propto 1/\gamma^2$)

Effects of beam space charge

- Space-charge forces in a beam arise from **mutual Coulomb repulsion** ($\propto \gamma^0$), cancelled in part by **magnetic attraction** ($\propto -\beta^2$)
- These forces limit intensity because of **phase-space dilution**, **beam losses**, and **radioactivation** of components
- In synchrotrons, losses depend on space-charge defocusing **tune shift**:

$$\Delta\nu \propto -\frac{Nr_0}{\beta\gamma^2\epsilon_n}$$

		tune shift	injection losses
Currently:	Booster	-0.30	15% or 300 W
	Main Injector	-0.03	1% or 200 W

For a given level of tolerable losses, **compensation of space charge** means **higher intensities** can be achieved

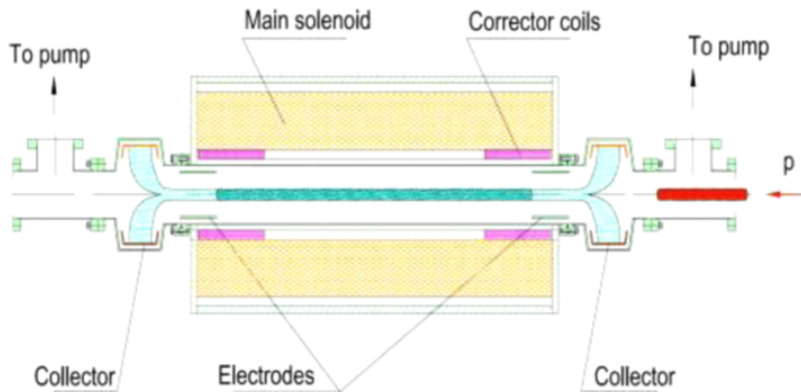
Requirements for space-charge compensation

- Coulomb repulsion can be mitigated if circulating protons are forced through a plasma cloud or **column of opposite charge**
- For full compensation, **required charge density** is (proton density)/ γ^2
At 8 GeV ($1/\gamma^2 = 1/90$) — 1/90 of charge density over whole ring, or same charge density over 1/90 of ring
For 8-GeV Project-X MI, $n_e \sim 10^9\text{--}10^{11} \text{ cm}^{-3}$
- Column density should have same transverse and, possibly, longitudinal **profile** as beam

Proposed solution:

With solenoid and electrodes, trap electrons from rest-gas ionization caused by the beam, constraining them to the radial position where they were generated

Electron column concept



Shiltsev, PAC07

Electron column concept

Design

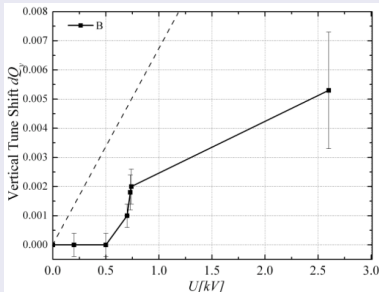
- Strong solenoidal **B** field (~ 1 T)
 - if Larmor radius of electrons is \ll than proton beam size
 \Rightarrow transverse size of column closely mimics beam density?
 - enhances radiation cooling of plasma
- Electrode voltage ~ 5 kV to trap enough charge
- Ionization rate $\sim 4 \times 10^{10} \text{ s}^{-1}$ (3 A of 8-GeV protons in MI, 10^{-7} mbar)
- Longitudinal charge distribution can be tuned by adjusting loading time of trap ($\propto \text{pressure}^{-1}$) compared to bunch length
- Plasma rotation around axis requires round beam at column locations

Issues

- Ions cause instability, must be free to leave trap
- Solenoid introduces coupling \Rightarrow skew quads or columns with opposite fields
- Stability of beam-column system?

Preliminary experiments

150-GeV protons in Tevatron (TEL solenoid and electrodes)



- Observed positive tune shifts vs electrode voltage above 5×10^{-8} torr
- Beam and vacuum instabilities

10-keV electron beam in test bench



- Observed charge accumulation
- Plasma oscillations

*V. Shiltsev, A. Valishev, G. Kuznetsov,
V. Kamedzhiev, A. Romanov, PAC09*

Research plan

- 1 study the physics of **electron column formation** and its **stability**
- 2 extend existing Booster **simulations** to evaluate **effects in MI and RR**
- 3 in test bench, **measure charge accumulation and stability** vs energy, intensity and time structure of beam; magnetic field; electrode voltage; and residual-gas pressure
- 4 **upgrade test bench** with plasma diagnostics and stabilizing electrodes
- 5 design **tests for Tevatron** at 150 GeV
- 6 if promising, design and build **prototype** for 8-GeV protons in Fermilab complex

Conclusions

- Started experimental and theoretical study of two new applications of magnetically confined electron columns to high-energy hadron beams:
 - **collimation** with hollow electron beams
 - **space-charge compensation** with trapped electrons from beam-induced rest-gas ionization
- Projects build upon interplay between several fields: vacuum tubes, electron cooling, electron lenses, nonneutral plasmas
- Suggestions and collaborations more than welcome!

Thank you for your attention